Rapid intensification and propagation of the dayside aurora: Large scale interplanetary pressure pulses (fast shocks)

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Abstract. We study cases of abrupt dayside auroral brightenings and very fast auroral propagation using the POLAR UV imaging data. The brightenings occur first at noon and then propagate along the auroral oval towards dawn and dusk. Ionospheric speeds of 7 to 17 km/s are determined. The auroral brightenings are associated with the arrival of interplanetary shocks/pressure waves. The speed of the auroral propagation corresponds extremely well to the solar wind downstream flow. Our model assumes that the shock /pressure wave compresses the low latitude boundary layer (LLBL) magnetospheric fields and plasma contained thereon. This plasma compression leads to the lose cone instability, wave-particle interactions and concomitant particle loss into the ionosphere. Several implications for this model are discussed.

1. Introduction

Identifiable feature of the dayside aurora can be used as crucial clues towards understanding how solar wind energy, momentum and charged particles get transported into the magnetosphere. One magnetospheric response to solar wind dynamic pressure variations is velocity vortices in the dawnside magnetopause (Sibeck, 1990). The formation of plasma vortices in the low latitude boundary layer (LLBL) by the Kelvin-Helmholtz instability leads to momentum (but not particle) transfer from the solar wind to the ionosphere (Wei and Lee, 1993). Dayside auroral bright spots (at around 14 MLT) and dayside auroral break-ups caused by high solar wind ram pressure or a dramatic increase in the pressure were studied by Lui and Sibeck (1991) and Sandholt (1987). Patchy magnetic reconnection at the dayside magnetopause results in the transport of magnetosheath particles onto closed magnetic field lines (Lee et al., 1988 and Karlson et al., 1996). Another mechanism for the physical transport of particles across the magnetopause is resonant (ELF) wave-particle interactions at the magnetopause with cross field diffusion onto closed field lines (Tsurutani and Thorne, 1982). Pitch angle scattering is thought to be sufficiently intense to lead to strong diffusion, with the resultant precipitation being a significant portion of the dayside auroral energy (Tsurutani et al., 1981). A further mechanism is impulsive penetration of solar wind plasma filaments through the dayside magnetopause into the magnetospheric boundary layer. This is suggested to occur under certain IMF orientations when these filaments have an excess momentum (Schindler, 1979; Heikkila, 1982).

The purpose of this paper is to explore a new dayside auroral phenomenon in which brightening is initiated by interplanetary shocks (or the increased solar wind ram pressure related to high speed streams). In this paper, we use the POLAR UV instrument data to present several rapid dayside auroral intensification and propagation events.

2. Observations of Interplanetary Shocks and Dayside Auroras

2.1 December 10, 1997 event

At 0430 UT December 10, 1997, the WIND spacecraft records an interplanetary (IP) shock in the upstream solar wind at 207 R_E. This is shown in Figure 1. The forward shock (with Mach number ~ 2.1) is identified by an increase of the interplanetary magnetic field, solar wind bulk speed, proton density and proton thermal speed. Based on the shock orientation and propagation speed (provided by Dr. D. Berdichevsky, private communication, 1998), we calculate that the IP shock should take ~ 53 min to travel from WIND to the Earth. It is predicted to arrive at the nose of magnetopause at ~ 0525 UT. The shock at WIND causes an increase in ram pressure P_{ram} (nmV_{sw}^2) from 1.5 to 6.5 nPa and an increase in dynamic pressure P_{dy} ($\frac{B^2}{8\pi} + nkT$) from 0.03 to 0.15 nPa. These are shown in the bottom two panels of the Figure 1. Although P_{dy} is much smaller than P_{ram}, the variation at P_{dy} is increased by 5 times. The flanks of the tail magnetopause are squeezed by a factor of 5 greater. According to the magnetic flux conservation in the tail lobe, the size of the lobe will be reduced ~1/3 in diameter by this increased dynamic pressure (see Ho and Tsurutani, 1997 and Kokubun, 1997 for distant tail examples). At the time when the shock arrived at the Earth, GEOTAIL was in the dawnside magnetosheath at about (-3.7, -25.1, -0.5 R_E) in GSE coordinates, slightly downstream of the Earth. A proton density increase from 35 to 65 cm^{-3} was recorded at ~ 0528 UT while the plasma velocity increased from 250 km/s to 360 km/s. The enhancement plasma velocity was mainly along the negative X axis. The magnetic field intensity rapidly increased from 8 to 16 nT. If we assume the nose of dayside magnetopause is at 10 R_E prior to shock arrival, the shock should take 4 min to propagate from the nose to the GEOTAIL position. The shock should therefore have arrived at magnetopause at ~ 0524 UT. This is basically the same time as determined by the extrapolation and calculation of the WIND data.

The dayside auroral brightening onset and subsequent propagation are shown in Figure 2, as viewed by the UVI. Typically, the UVI obtains an image every ~3 min with the same wave-bandwidth interference filter and with the same exposure time. In Figure 2, the images come from the LBHS filter, covering the wavelength band of ~140 -160 nm. Time evolves from panel (a) to (f) (top down and then to the right). The bottom color bar shows the auroral intensity in photons cm^{-2} s^{-1}. The near-noon auroral brightening is first detected in panel (c) when the near-noon auroral intensity suddenly increased by a factor of 3-4 (panels (a) and (b) are shown for comparison). The brightening is obviously an effect of the arrival of the IP shock. The IP shock arrived between 0523:24 UT and 0526:28 UT. Thus, there is an excellent agreement in timing with our calculation of the shock arrival, either from WIND or from GEOTAIL. From panel (c) to (d), the eastern edge of the bright aurora propagates along ~74° magnetic latitude towards east. And at the western edge, it propagates along ~ 76° magnetic latitude towards the west (westward means clockwise, eastward means anti-clockwise looking down over the north pole). The eastern edge of the brightening moves from ~13 MLT to ~18 MLT and the western edge from ~9:30 MLT to ~ 4:30 MLT. The western brightening intensity is double that of the eastern brightening (at panel (d)). The longitudinal (along the oval) propagation speed in the ionosphere can be calculated. The average longitudinal speed of the eastern edge from one image to next 3 min later is ~ 12.5 km/s. The average speed western edge is ~ 11 km/s. From panel (d) to (e), the aurora continued to propagate antisunward and even reaches the midnight sector (from 21 MLT to about 2 MLT). At panel (e), when the eastern edge arrived at ~ 22.5 MLT, and using 72° as an average latitude, the aurora longitudinal propagation speed is ~ 12.7 km/s. The western edge of the aurora arrives at ~ 1:30 MLT at panel (e). Using 73° as an average latitude, the calculated longitudinal propagation speed is ~ 8 km/s. In panel (e), the illumination is intensified by a 3-4 factor over that at panel (c) at both flanks.

2.2 January 10, 1997 event

Another fast dayside auroral event is the January 10, 1997 event. An IP shock (with Mach number ~ 1.5) is observed by WIND at 0052 UT at an upstream distance of ~85 R_E. This is discussed in Tsurutani et al. (1998a) and Arballo et al. (1998). As shown in Figure 3, the auroral brightening occures at a time between 0100:44 and 0103:48 UT. The calculated shock arrival time is ~ 0103 UT, which is again obtained by a calculation based on the shock orientation and propagation speed. As shown in panels (c) and (d), the noon aurora expands towards both east and west, while the auroral intensity increases about a factor of 2. The eastern edge propagates from ~ 12 MLT at ~ 0104 UT to ~ 15 MLT at ~ 0107 UT along 75° average magnetic latitude (actually the aurora is spread over a 70°-80°

MLT region). The average longitudinal propagation speed is ~ 7 km/s. With a similar speed, the eastern edge eastward propagates continually and reaches 16 MLT at 0110 UT (panel (c)). The western edge of the noon aurora in panel (c) propagates along the dawnside oval from ~10 to ~4 MLT (Sandholt et al., 1998) (as shown in panel (d)). Using 72° as an average latitude, the average auroral longitudinal propagation speed is ~ 17 km/s. From panel (e) to (f), both duskside and dawnside auroral brightenings are intensified by about a factor of 2.

3. Model and Discussion

The dayside auroras shown in Figures 2 and 3 propagate very fast away from local noon. The aurora longitudinal propagation speed in the December 10, 1997 event is ~12 km/s at duskside and ~ 9.5 km/s in the dawnside (on average). For the January 10, 1997 event, the dayside aurora propagates at ~ 7 km/s in the duskside. The western edge of the intense aurora moves at ~17 km/s from 10 MLT to 4 MLT.

Our model for this auroral brightening and rapid propagation is that the increased solar wind ram and dynamic pressure from the shock/pressure wave first compresses the LLBL and magnetosphere. The compression first occurs at the magnetopause nose (~12 MLT) and then expands towards dawn and dusk as the shock/pressure wave moves downtail. Assuming that the first adiabatic invariant is conserved, compression of the LLBL field lines leads an increase in perpendicular kinetic energy ($\varepsilon_\perp$) of the electrons on those field lines. The enhanced $T_\perp/T_{/\!/}$ of the distribution function will result in the loss cone instability. The growth of electromagnetic whistler mode waves (Tsurutani et al., 1998b) leads to enhanced electron pitch angle scattering, filling of the particle loss cone, and results in electron loss into the upper ionosphere. The dayside auroral magnetic latitude location and region in ionosphere should correspond to the L shells which have been strongly affected by the compression of the magnetosphere. In this scenario, the location and propagation of the dayside auroral forms should result from the location and propagation of the compression of the LLBL. This process is illustrated in the schematic in Figure 4. When a planar shock or solar wind pressure pulse arrives at the nose of the magnetopause, the magnetopause is compressed and moves earthward. This is indicated in the first two panels. When pressure balance between the magnetospheric fields and the solar wind is achieved, the earthward motion of the magnetopause will cease. The ram pressure and the increased dynamic pressure both squeeze the magnetopause inwards towards the Earth on the flanks (when the ram pressure is not perpendicular to the normal of the magnetopause). Therefore a bending (A and A′ at t_3) will be formed at the front of the shock/pressure wave. The magnetospheric compression propagates in the down-tail direction along with the shock/pressure wave down-tail propagation. Wherever the fields are compressed, the loss cone instability will occur (assuming that there are sufficient pre-existing fluxes of trapped particles) and cause auroral brightening. When the compression position propagates with the high speed plasma flow down to the tail (with temporal sequence t_1 to t_3), this brightening represents an auroral expansion and propagates along the oval towards both the dusk and the dawn flanks (and can even enter the night sector).

In this scenario, if we assume that the LLBL magnetic field lines are closed and map to the outer magnetosphere, magnetotail at the same local time, the propagation of the compressed magnetopause position should be at a speed which is aligned with the speed of the auroral propagation. For the December 10, 1997 event, the dawnside auroral propagation speed is ~ 9.5 km/s on average. Then corresponding speed along the magnetopause should be ~367 km/s. This speed is in good agreement with the record of GEOTAIL magnetosheath speed of 360 km/s.

4. Implications of the Results

We have shown abrupt auroral brightenings and rapid motion from noon to dusk and noon to dawn. The brightening were associated with the arrival of IP shocks at magnetopause . The rapid longitudinal auroral propagation towards both flanks are matched with the speed of the interplanetary shock or the high speed pressure pulse moving tailward. We predict that these rapid dayside aurora onsets and global ionospheric propagation events are present in ground all-sky camera or photometer scanner data. Such fast speeds have been seen by Viking UV imager and ground based magnetometer (Elphinstone et al., 1991).

When an IP shock or a solar wind pressure pulse impinges the Earth magnetopause, fast auroral propagation should occur starting from local noon towards the dawn and dusk flanks. The speed will vary from event to event and depends on the speed of the interplanetary event. Interplanetary velocities three times greater than the events reported here have been previously discussed in the literature. The intensity of auroral brightenings depends on the increase in ram and dynamic pressure of the interplanetary events and the preconditions of the magnetosphere. Clearly the fastest interplanetary events will have the greatest ram pressure and one would expect the most dramatic auroral effects. We are currently looking into the events present in the WIND data set to determine the (shock to shock) variations in the auroral effects.

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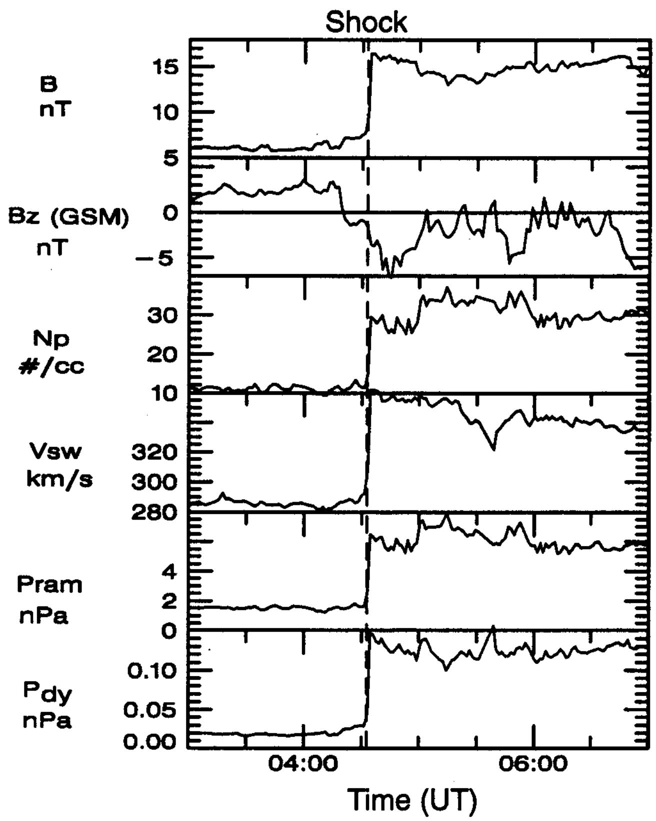
Figure Captions

Figure 1. The interplanetary shock recorded by WIND on December 10, 1997. At the shock time (~ 0432 UT) WIND was in upstream solar wind at (207, 11 22 R_E) in GSM coordinates.

Figure 2. Rapid dayside auroral propagation event on December 10, 1997. The images come from the LBHS filter (~140-160 nm) with 36.8 sec exposure time. Magnetic coordinate system is used with noon at top and dawn at right. The dayglow and background noise have been removed from the images. Time evolves form panel (a) to (f). Panel (c) shows the aurora onset just after the shock arrival.

Figure 3. Rapid dayside auroral propagation event on January 10, 1997. The images come from the LBHL filter (~170 nm) with 36.8 sec exposure time. Magnetic coordinate system is used with noon at top and dawn at right. The dayglow and background noise have been removed from the images. Time evolves form panel (a) to (f). Panel (c) shows the aurora onset just after the shock arrival.

Figure 4. A sketch of magnetopause compression by IP shock or by solar wind pressure pulse. This is a intersection in meridional plane. Magnetopause is compressed and a bending (as shown at A and A') is formed when IP shock or pressure pulse arrives and propagates down tail at a temporal sequence from t_1 to t_3. The dot line is the original magnetopause position before the compression.


Shock
B
nT
15
10
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Bz (GSM)
nT
0
−5
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30
20
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Vsw
km/s
320
300
280
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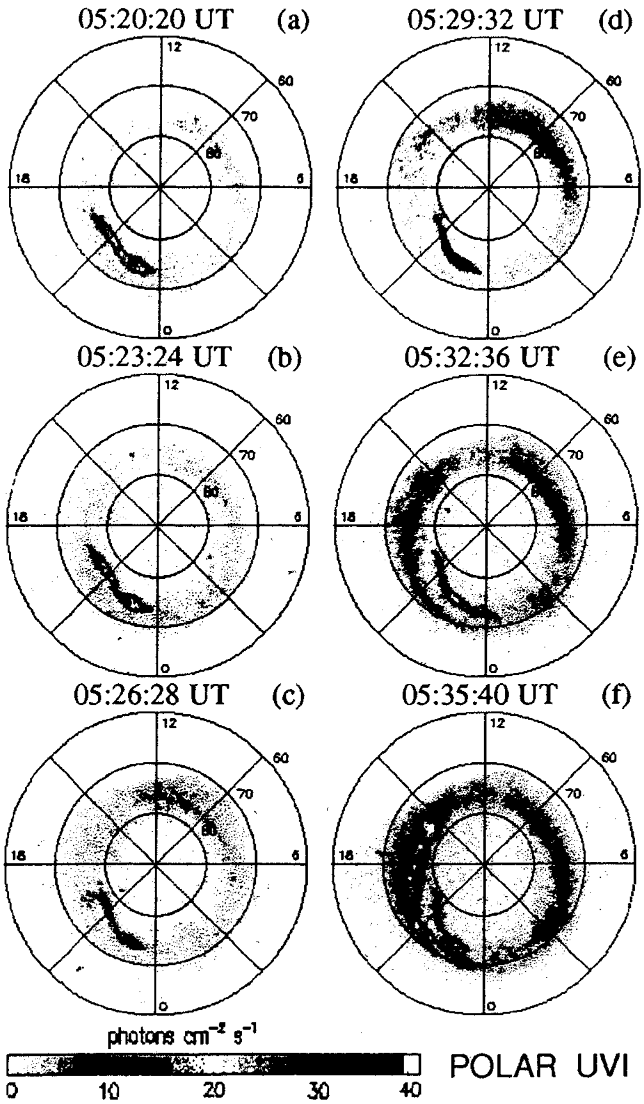
04:00
06:00
Time (UT)

Fig. 1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05:29:32 UT (d)
05:23:24 UT (b)
05:32:36 UT (e)
05:26:28 UT (c)
05:35:40 UT (f)
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18
6
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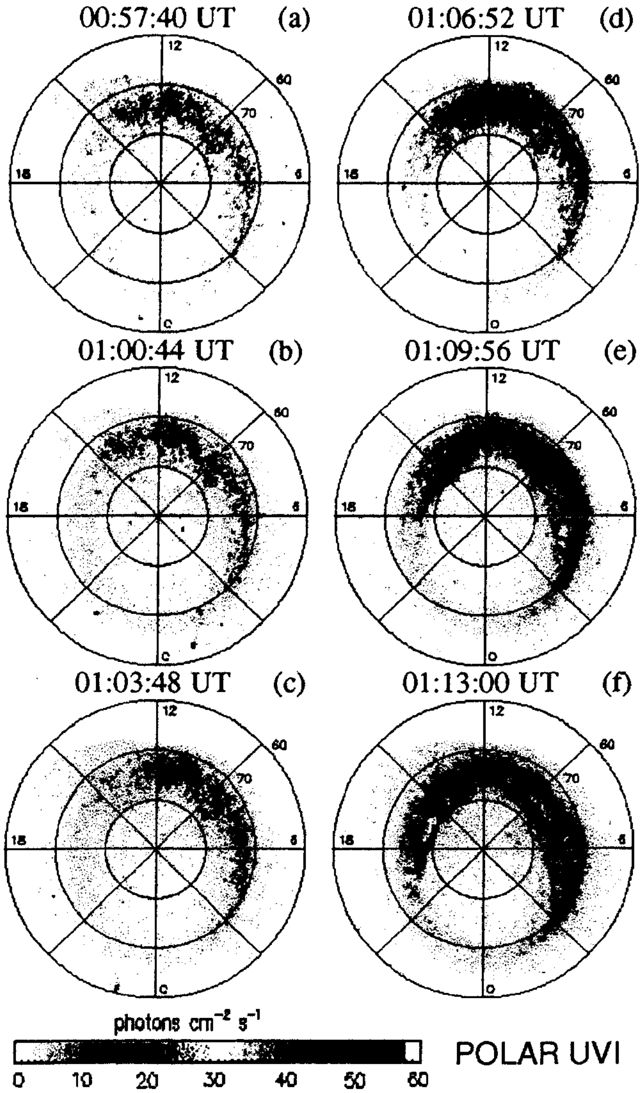
60
70
80
photons cm^{-2} s^{-1}
0 10 20 30 40
POLAR UVI

Fig 2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01:03:48 UT (c)
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photons cm^-2 s^-1
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0 10 20 30 40 50 60

Fig 3.

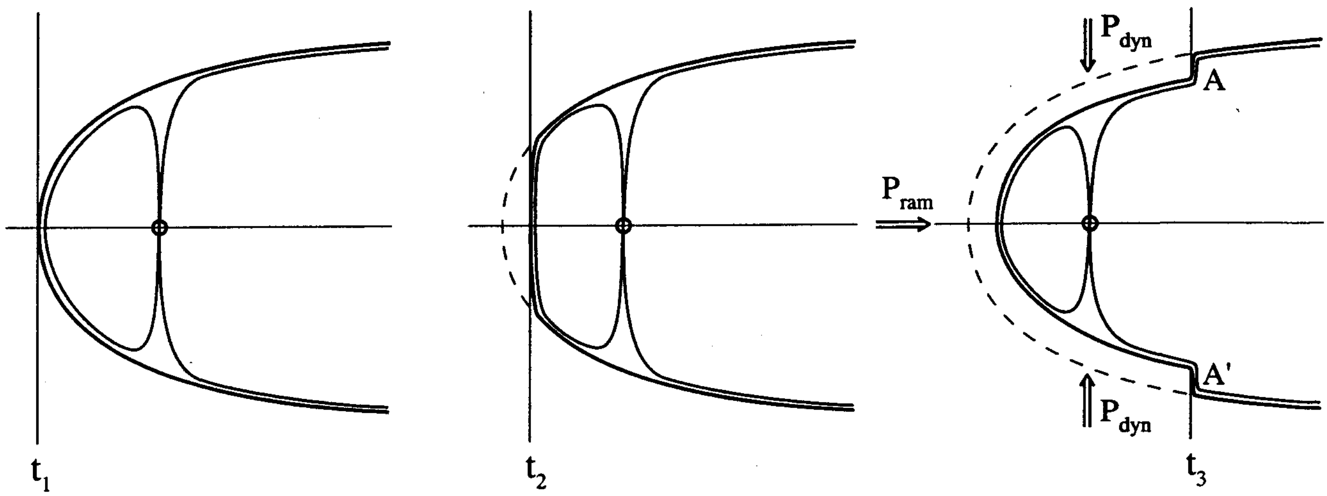

Fig. 4